Sentinel-1 Doppler: progress, challenges, and perspectives

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Sentinel-1 Doppler Centroid Anomaly

$$f_{dca} = \underbrace{(\overset{\text{Sea State}}{\downarrow} f_{ss} + \overset{\text{Surface Current}}{\downarrow} f_{osc})}_{\text{Geophysical}} + \overbrace{f_{bias} + f_{att} + f_{sca} + f_{temp} + \Delta f}^{\text{Non-geophysical}}$$

How to retrieve geophysical Doppler?

- **Challenge #1:** Re-calibrate data removing all non-geophysical contributions
- **Challenge #2:** Partition geophysical signal between different contributions (sea state, current, etc.)
- **Challenge #3:** Interpret and validate geophysical retrievals and estimate the uncertainty

Challenge #1: Sentinel-1 Doppler calibration strategy

Gilles Guitton

Quick History

- 2014 - S1A Launch: calibration based on attitude DC from AOCS quaternions and antenna model
  - ➜ Both were not able to describe the variations observed in DC
- AOCS optimization at STT level (light aberration correction and STT misalignment)
  - ➜ Improved the pointing but AOCS quaternions still not able to reproduce observed variations
- 2018: Start of the dedicated project "S1 RVL assessment"
  - ➜ Gyro data able to capture fast DC variations. Definition of a new calibration approach.
- Now: a dedicated processor is able to generate auxiliary calibration files containing DC attitude and DC bias
  - ➜ Plan to generate a large calibrated dataset in end 2023 / early 2024 (S1 MPC framework)
  - ➜ Calibration workflow still needs to be adapted for temperature compensation jumps

Current calibration strategy

- Non-geophysical Doppler is partitioned into:
  - DC Attitude: includes fast attitude variations (learned from Gyros) and slow orbital attitude variations (learned from WV DC observations)
  - DC Bias: includes electronic mispointing, thermo-elastic effects on antenna and mean attitude error
- DC Bias depends on acquisition mode:
  - WV mode: DC bias is computed when WV DC observations are used to refine attitude
  - TOPS mode: DC bias is computed from land acquisitions (L1 annotated Doppler)
- Except for the gyros part, the calibration relies mainly on DC observations. These observations are aggregated at daily scale providing daily calibration files.

Challenge #1: Sentinel-1 Doppler attitude and bias

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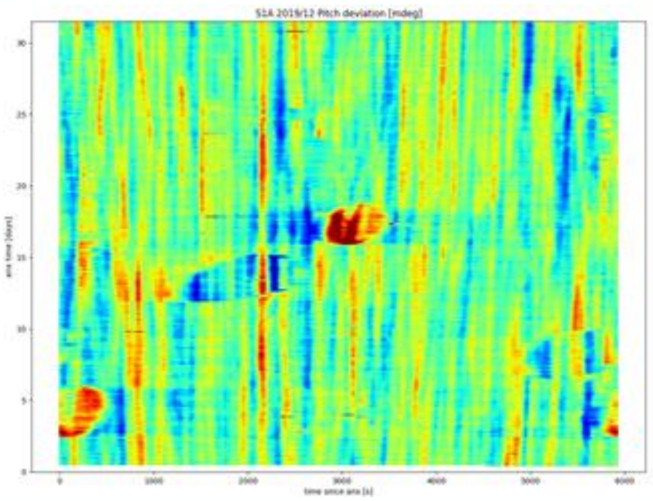
DC Attitude

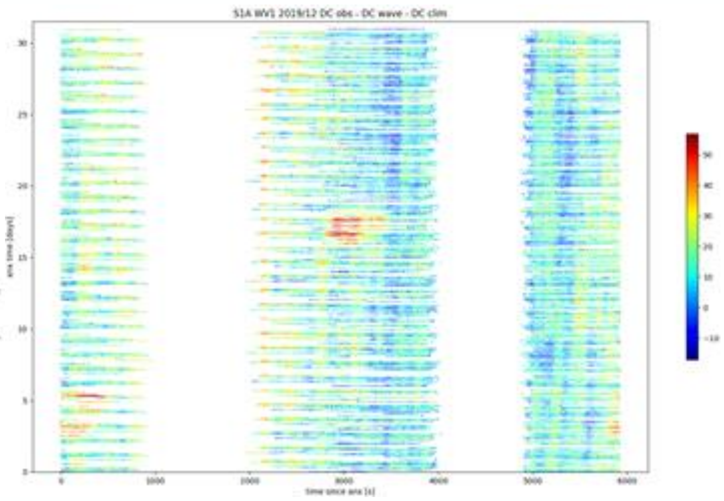
Gyros are able to catch fast DC variations due to attitude

Good agreement between:

- (left) Gyro-derived Pitch deviation from nominal law in millidegrees
- (right) WV1 DC observations after removal of a geophysical estimation in Hz

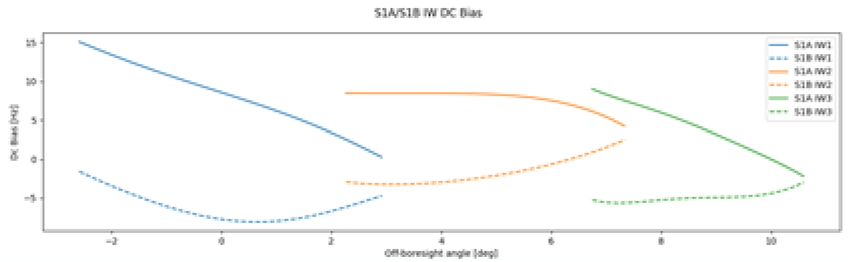
For S1, 1 mdeg in Pitch = 4.8 Hz in Doppler !

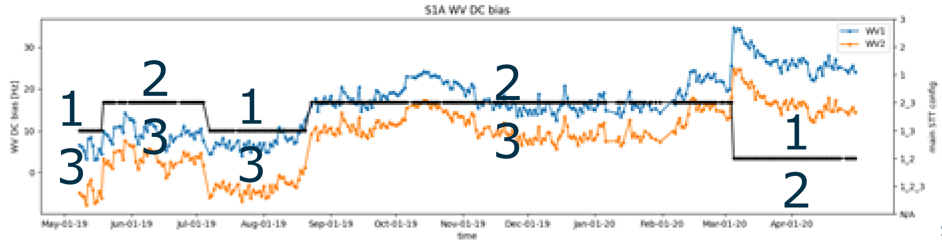




DC Bias

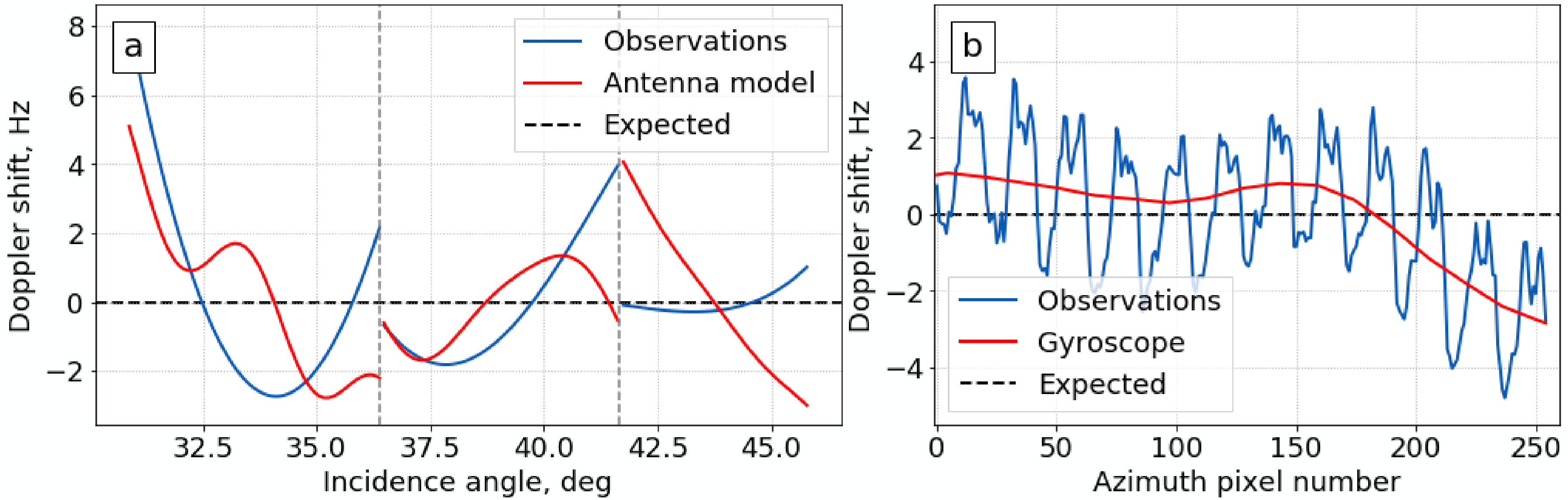
- The many IW land acquisitions allow to nicely learn the “range” bias as shown in top figure for the 3 IW subswaths of S1A and S1B
- Bottom figure shows one year of S1A WV1/WV2 DC bias:
  - Jumps are correlated with change in main STT pair in use (black line) (only true for S1A)
  - Seasonal variations are more likely due to thermo-elastic effects on antenna
- The data driven approach does not allow to separate easily what comes from attitude or from antenna.





Challenge #1: Sentinel-1 Doppler calibration evaluation

Sentinel-1B IW Doppler over Amazon rain forests (2017-12-28 23:11):



Residual Doppler shift after calibration is about 3-4 Hz (for WV and IW) corresponding to 0.15 - 0.25 m/s radial velocity

2 times better than the previous version

Challenge #1: Future Sentinel-1 Doppler calibration

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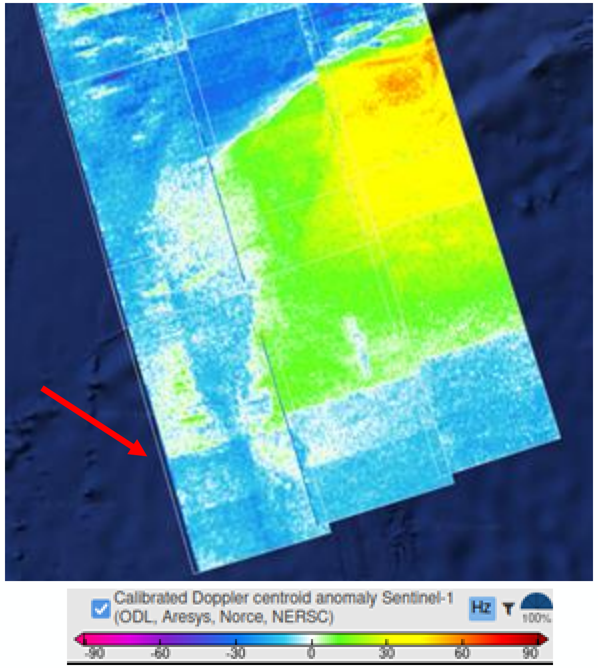
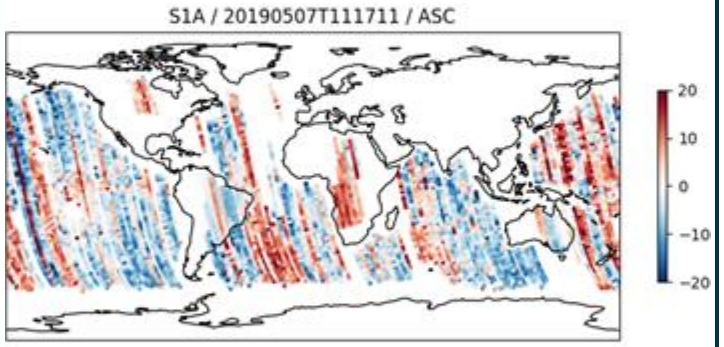
Next Challenge: Temperature Compensation

- Onboard temperature compensation is responsible for thermo-elastic distortion of the antenna. This may create some rapid pointing variations creating DC jumps when triggered.
- Left image shows such a jump in a IW acquisition
- Right image shows residual Doppler from S1A WV observations during 12 days. The variability between WV datatakes is suspected to come from jumps that happened during TOPS acquisitions (to be confirmed)





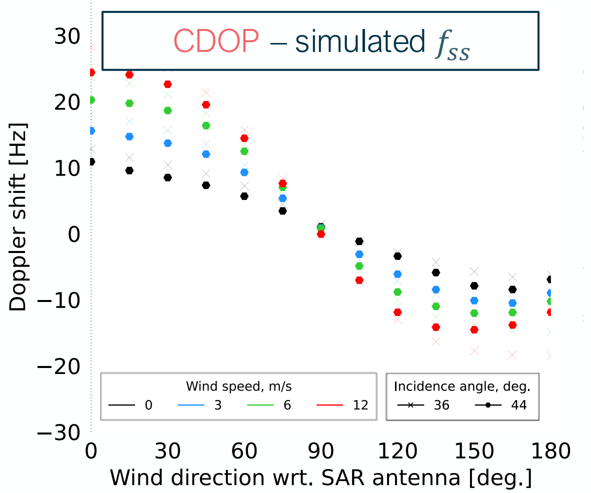
Next Challenge: Sentinel-1 C

- S-1C has a different AOCS system (better star tracker, less good gyro)
- Will the attitude steering still follow AOCS errors at high frequency ?
- Is the new AOCS system be able to capture rapid attitude variations (as was possible with S1A/B gyros) ?

Challenge #2: Sea State Doppler

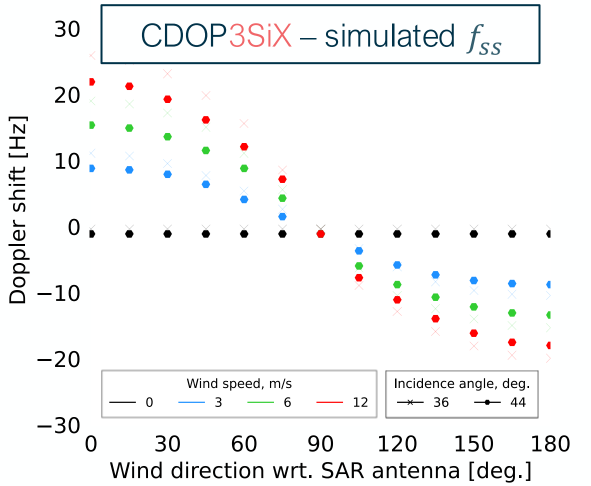
Original idea: Use an empirical GMF to predict the wind-wave-induced Doppler shift for the given wind field and radar configuration (based on Envisat):

$$f_{ss} \approx f_{ww} = \mathrm{CDOP}(u_{10}, \phi, \theta, p)$$

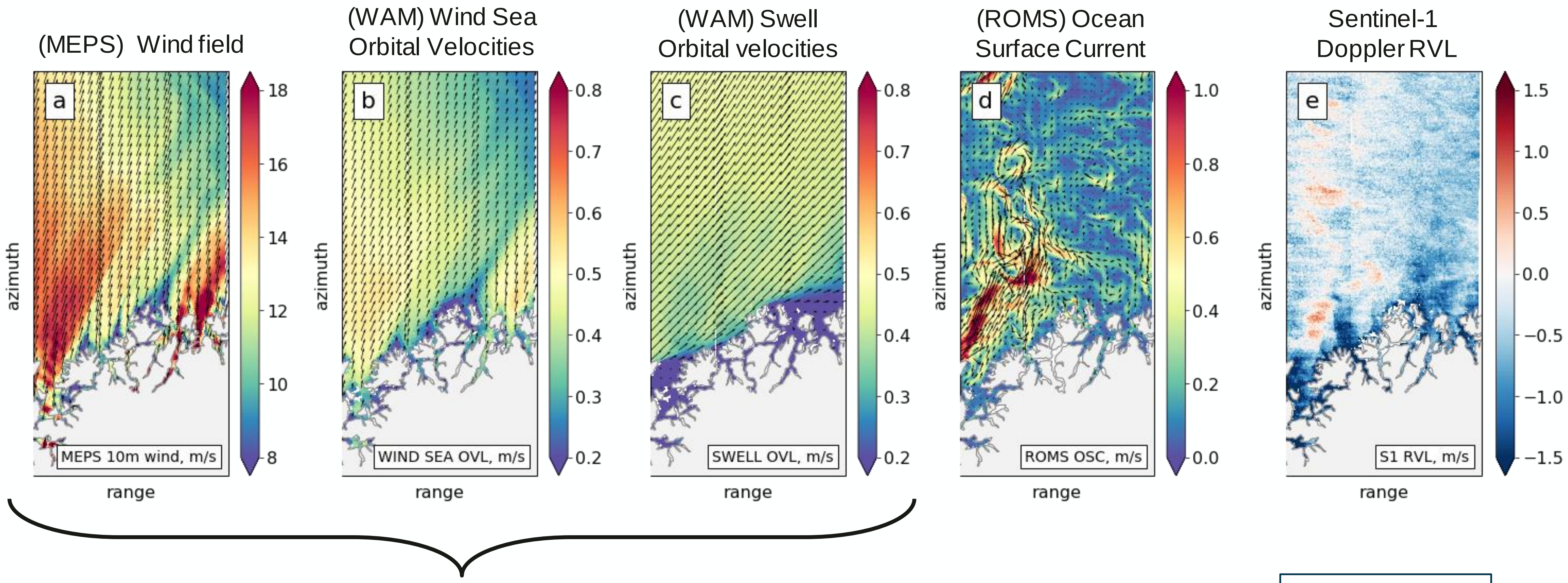


New idea: Add range directed the wind sea (x_{ws}) and swell (x_{sw}) orbital velocity to provide more realistic representation of the sea state (based on Sentinel-1:

$$f_{ss} = \mathrm{CDOP3SiX}(x_{10}, \underbrace{x_{ws}, x_{sw}}_{\text{Wave model}}, \theta, p)$$



Challenge #2: Sea State Doppler (coastal)

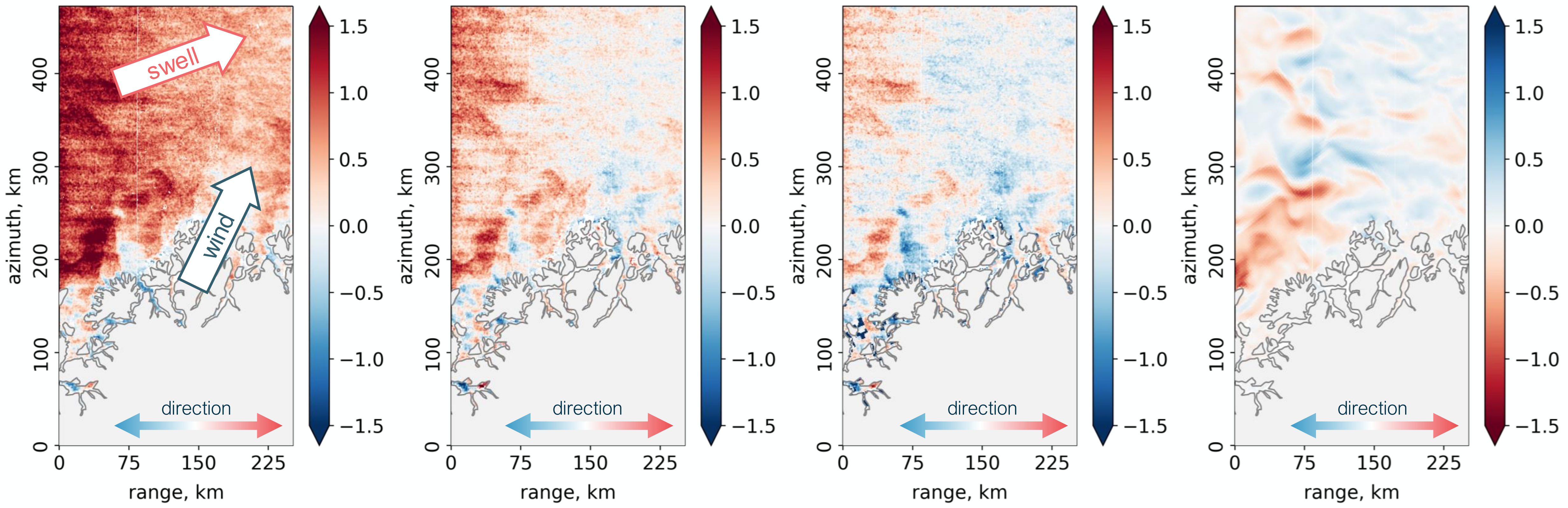


$$f_{ss} = \mathrm{CDOP3SiX}(x_{10}, x_{ws}, x_{sw}, \theta, p)$$

Northern Norway

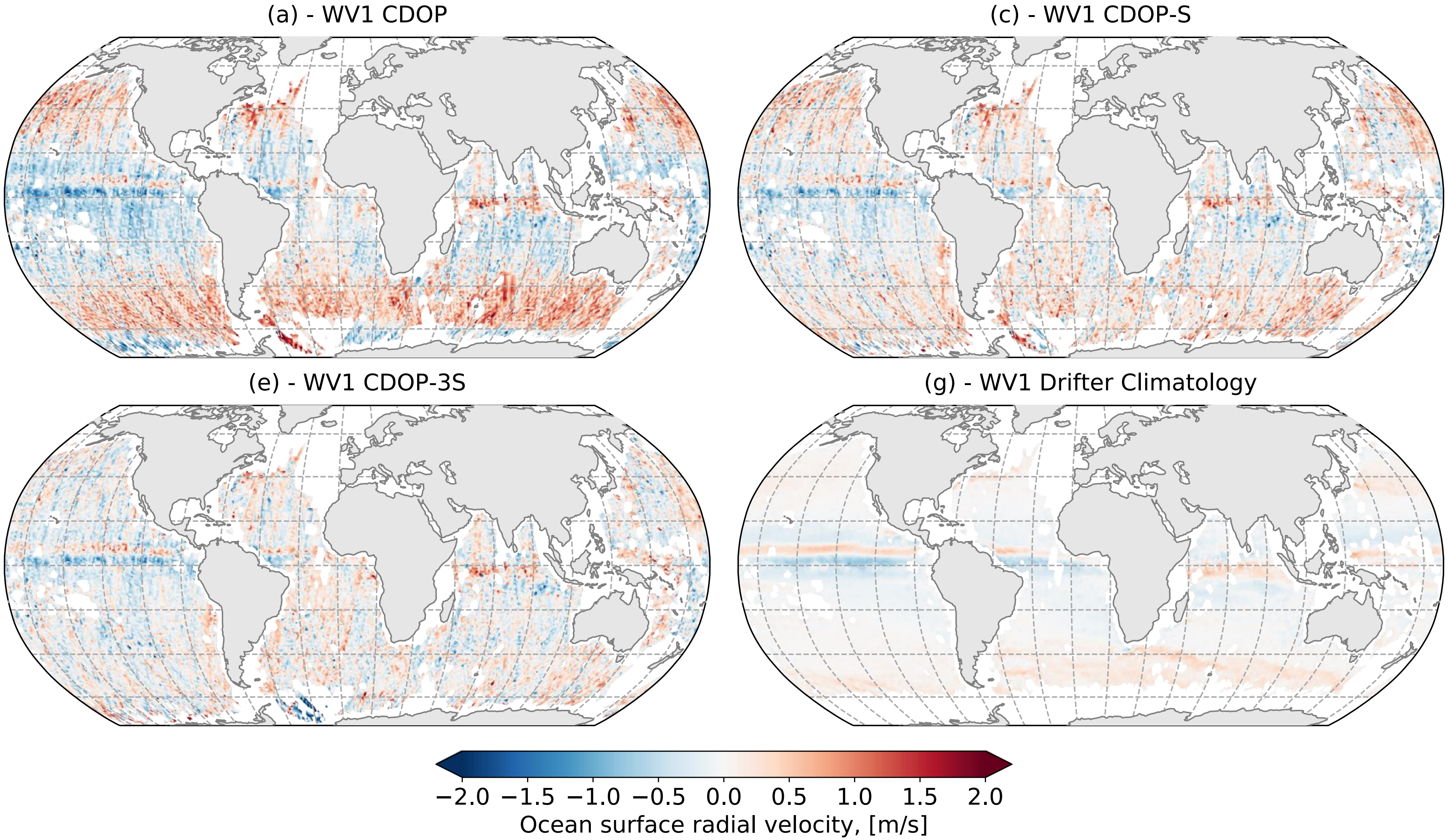
Challenge #2: Sea State Doppler (coastal)

Total Surface Motion (sea state + current)	Surface Current - old (total - CDOP)	Surface Current - new (total – CDOP3SiX)	Surface Current - model (ROMS NorShelf)



Northern Norway

Challenge #2: Sea State Doppler (global)



Challenge #2: Future Sea State Doppler

- Main constrain of existing GMFs is reliability of auxiliary information from model forecasts:
  - Model errors which are inherited by GMF during training/application
  - Availability of the similar model products globally (including coastal) with desired resolution

$$f_{ss} = \mathrm{CDOP3SiX}(\underbrace{x_{10}, x_{ws}, x_{sw}}_{\text{Wind/wave model fields}}, \theta, p)$$

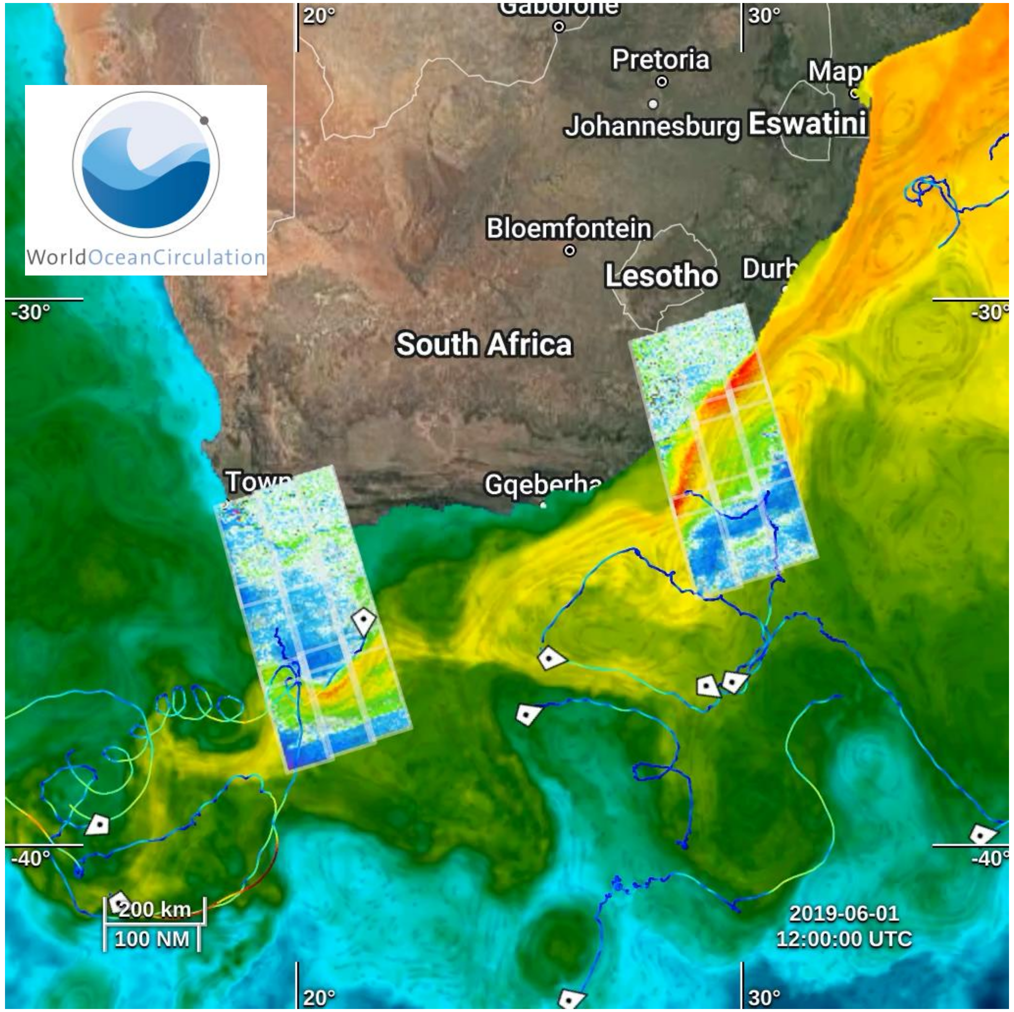
- Use wind/wave signal in SAR cross-section to estimate sea state contribution to the Doppler
  - SAR Cross-spectra contains information about the range directed wave motion at wide range of wavelengths
  - CS is routinely available for WV, but will also become available for the IW thanks to ESA SARWAVE project

$$f_{ss} = \mathrm{CDOPiMACS}(\underbrace{m_1, m_2, \ldots, m_n}_{\text{Integrated SAR cross-spectra parameters (a.k.a. MACS, iMACS)}}, \theta, p)$$

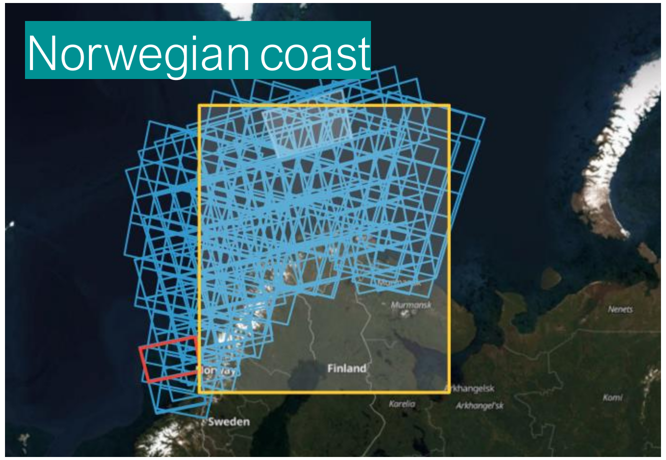
see Li et al. 2019, 2021

Sentinel-1 L2 OSC RVL product

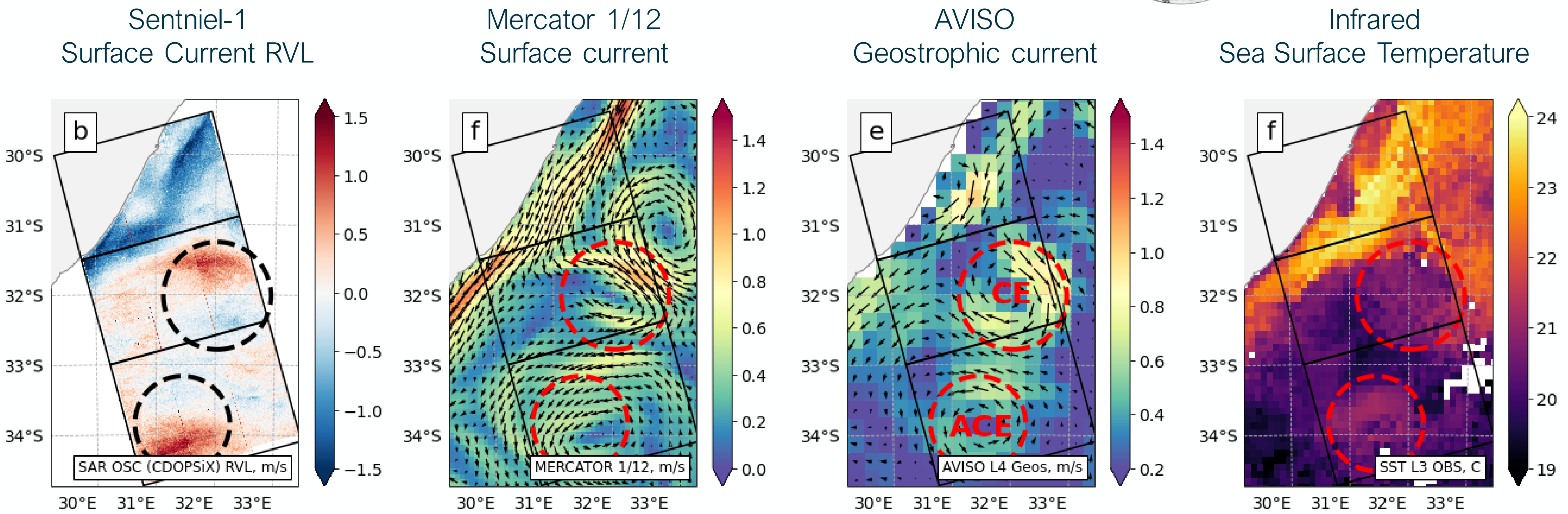
Sentinel-1A/B IW OSC RVL - Agulhas current



- Sentine-1A/B IW L2 Ocean Surface Current (OSC) Radial Velocity (RVL) product
- Based on the latest achievements in terms of calibration and signal partitioning
- Available from ESA World Ocean Circulation (WOC) project
- Will be updated



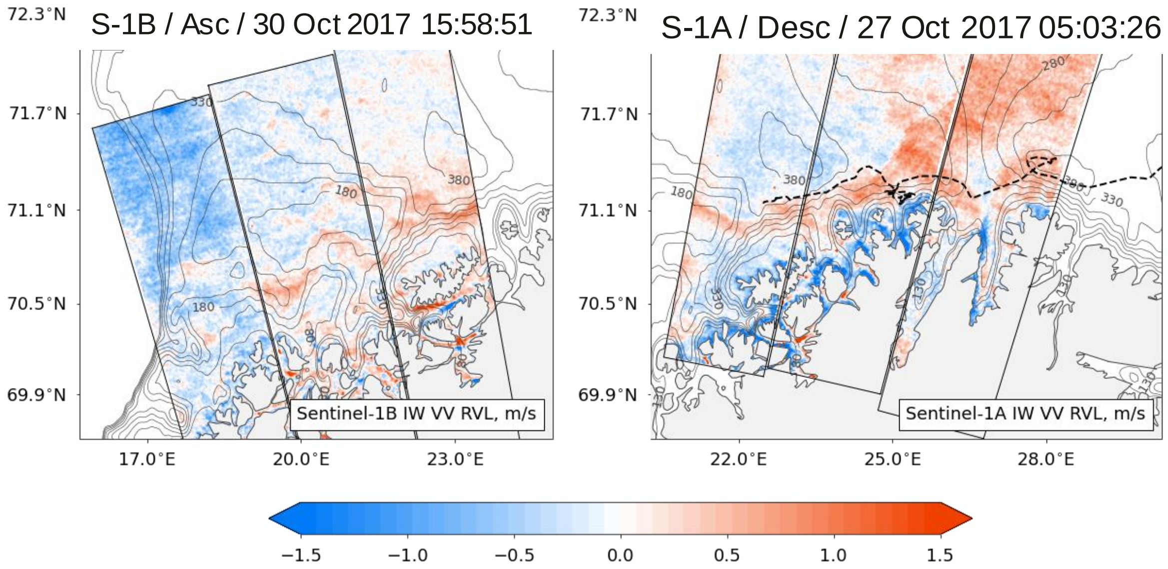
Challenge #3: Validation



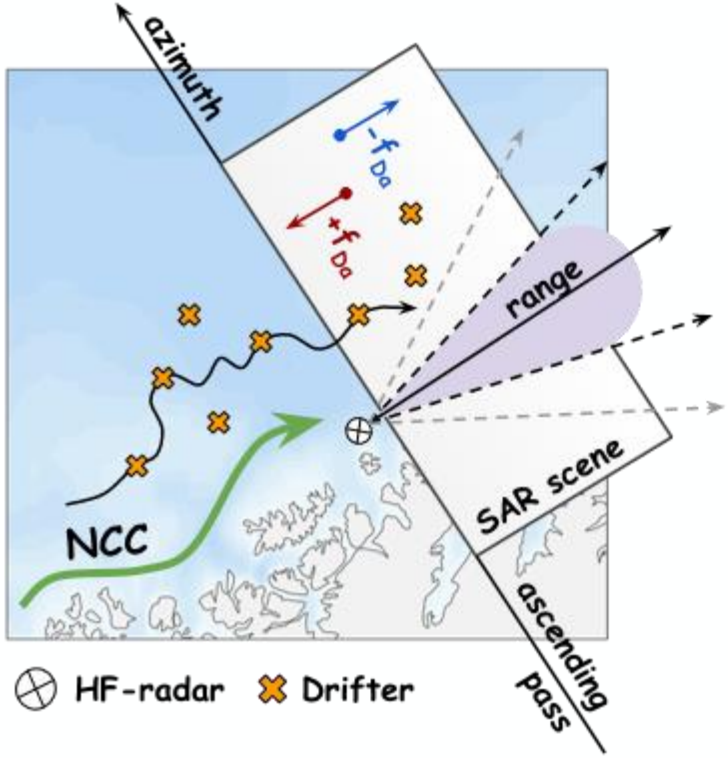
Sentinel-1A IW VV ascending pass on 14 July 2019

Challenge #3: Evaluation Against HFR Surface Currents

1. Evaluation against HFR observations:
   - 15 SAR scenes collocated
   - Good agreement in 7 cases with RMSD of 0.20 to 0.29 m/s
2. Evaluation against surface drifter observations:
   - Coastal current pattern is consistent with drifter trajectories
   - 6 SAR scenes collocated with at least 5 independent drifters
   - Good agreement in 5 cases with RMSD of 0.17 to 0.30 m/s



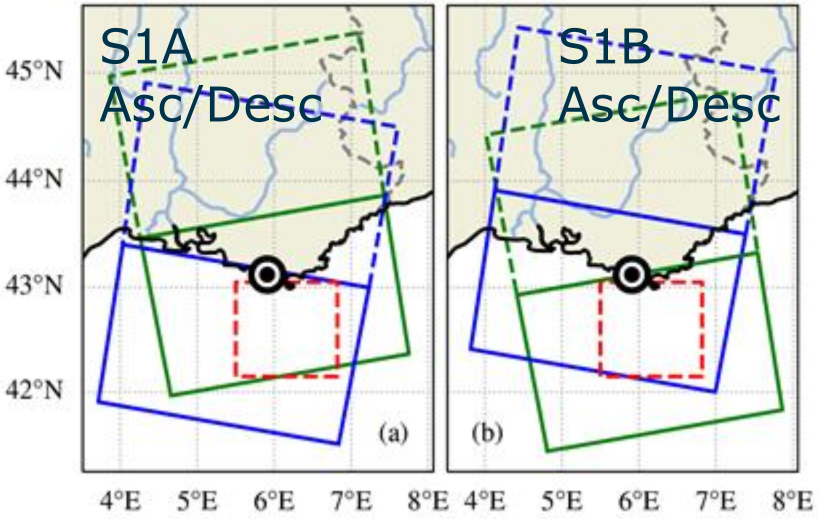
Scheme of SAR, HFR, and drifter collocation

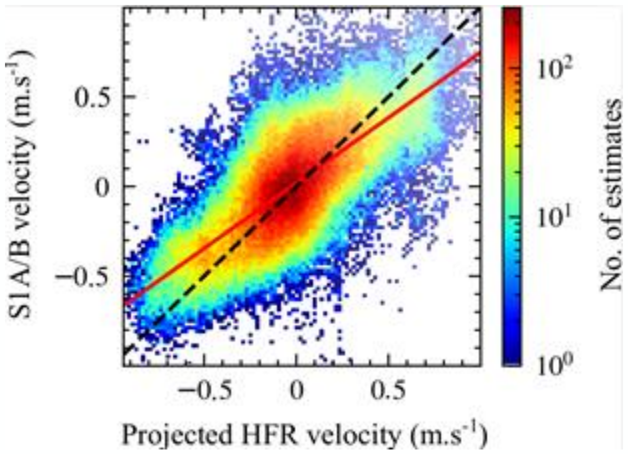


Data	Spatial	Temporal	Error
HF-radar	5 km	1 hr.	**0.25 m/s**
CARTHE	-	5 min.	**0.06 m/s**

Challenge #3: Evaluation Against HFR Surface Currents

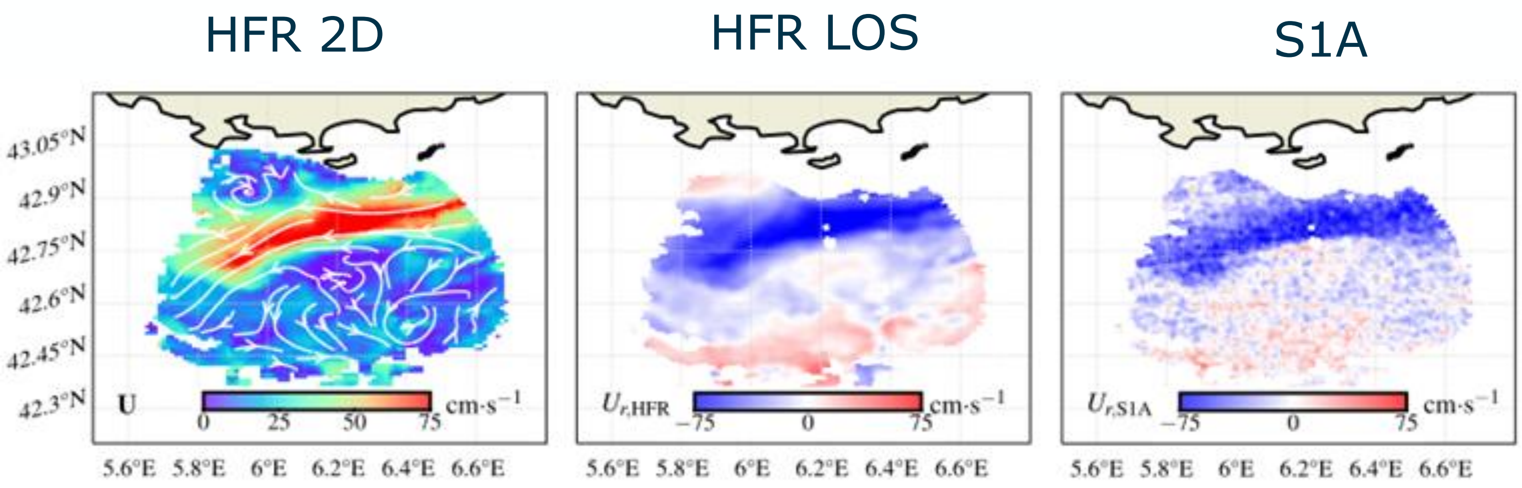
Baptiste Domps





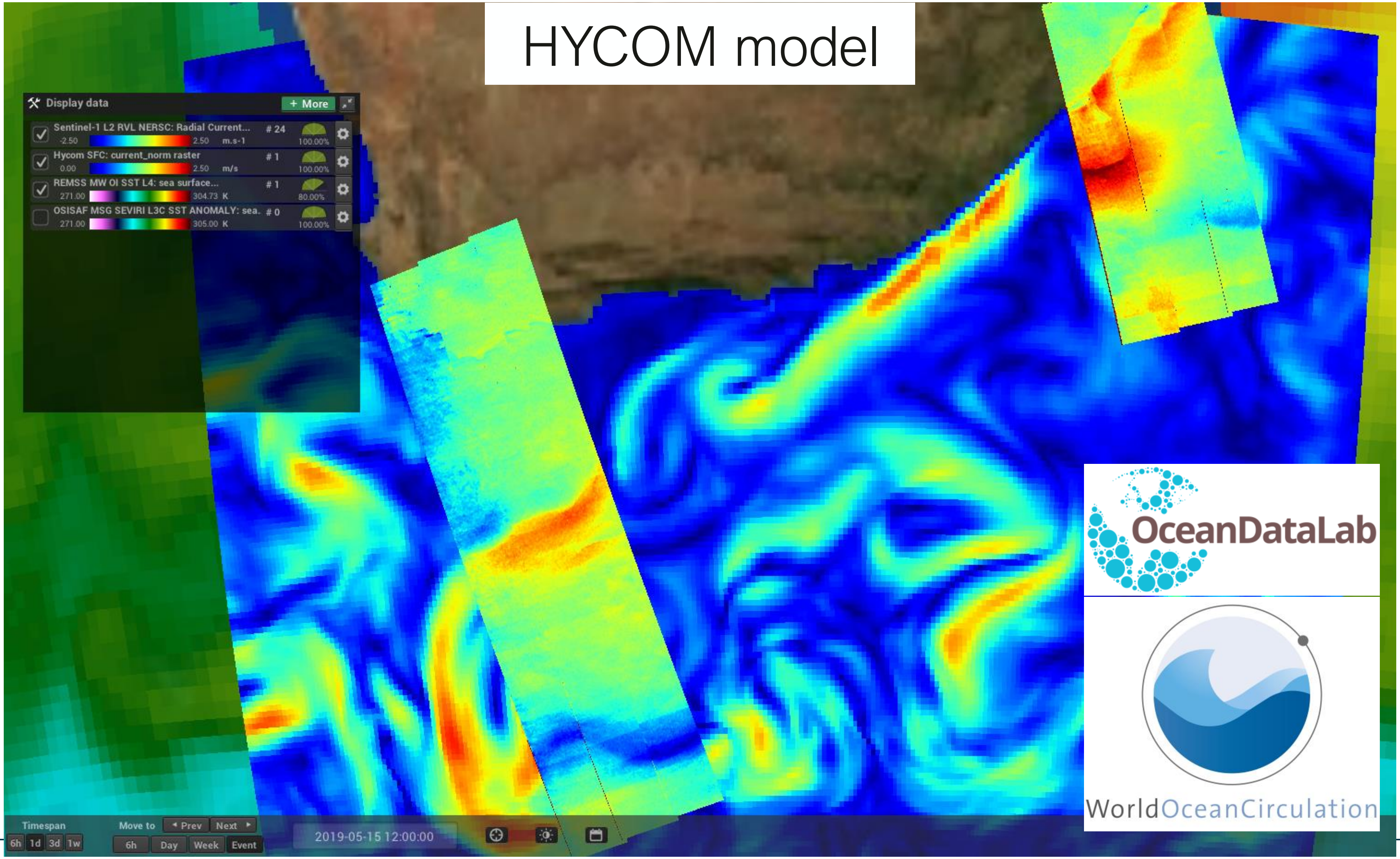
$y = 0{,}71x + 0{,}02$

- Assuming same vertical integration depth
- Multistatic HF Radar Network of Univ. Toulon, south of France (Prof. C.A. Guérin), calibrated using drifters [Dumas et al., 2021]
- 6 months of measurements (July 2020 to March 2021)
- Approx. 150,000 pixel-to-pixel comparisons : RMSE of 21 cm.s-1
- E.g. Northern Mediterranean Current on March 1st, 2021, 1730Z



- Playground for Cal/Val and new processing techniques

Challenge #3: Validation



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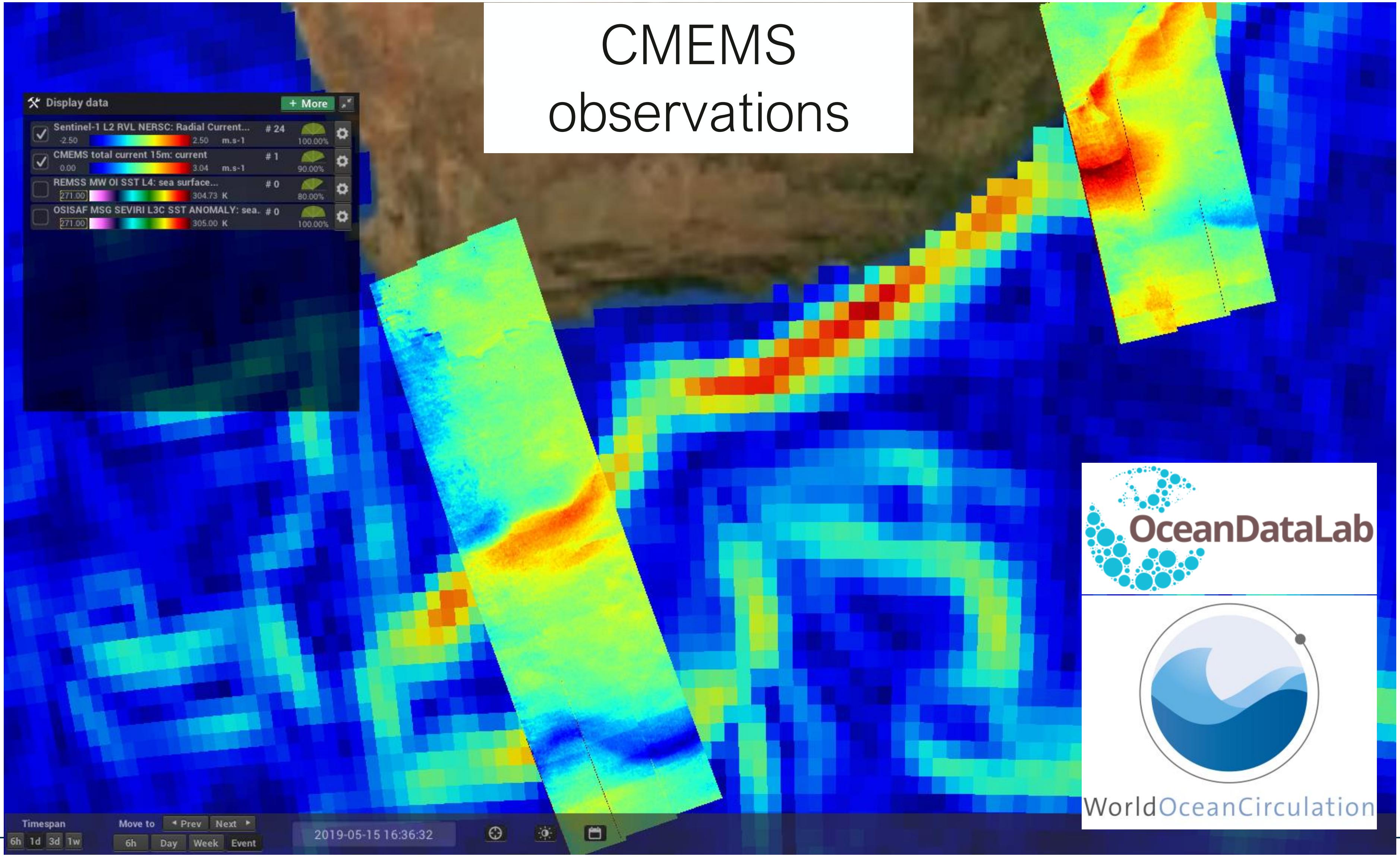

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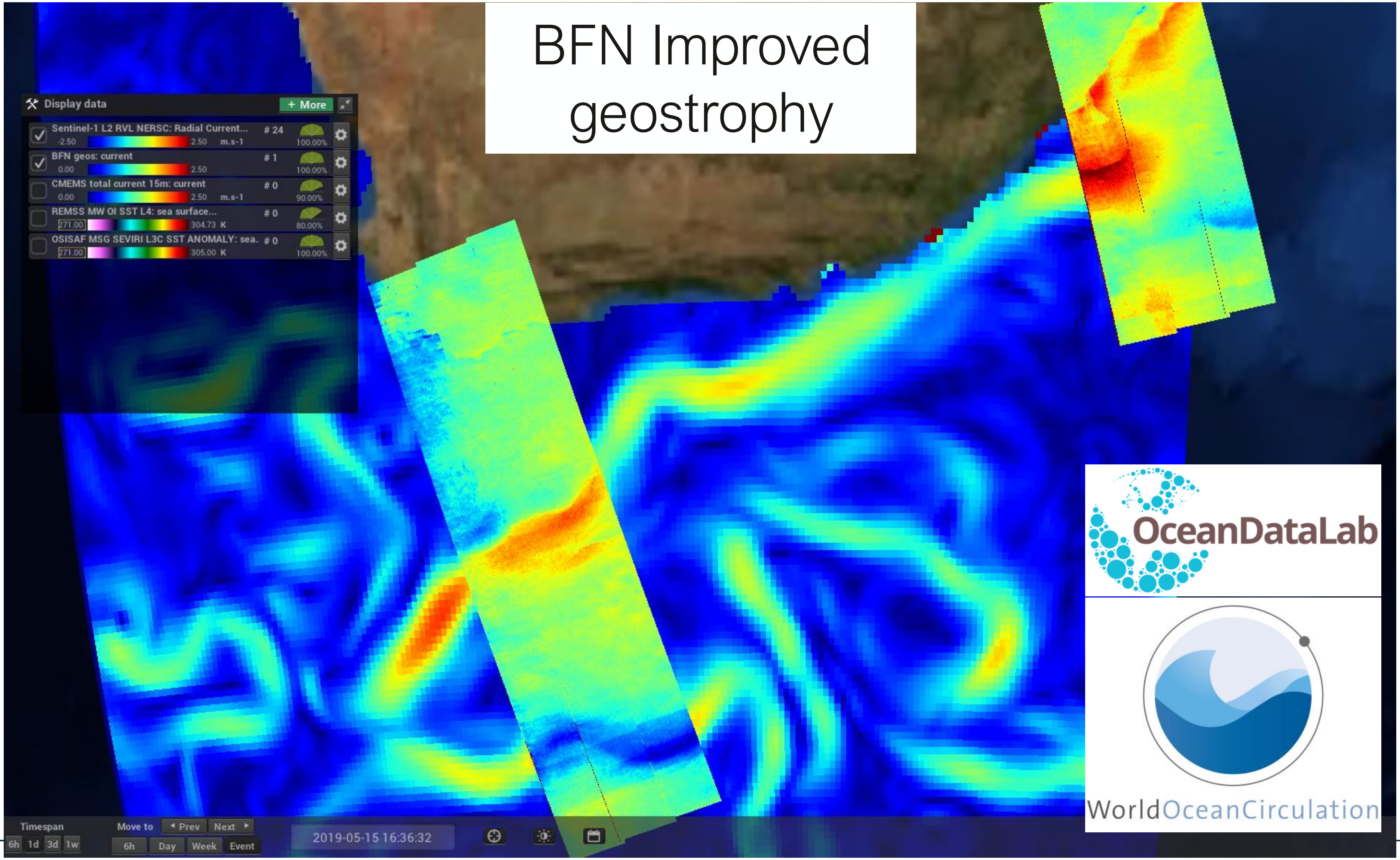

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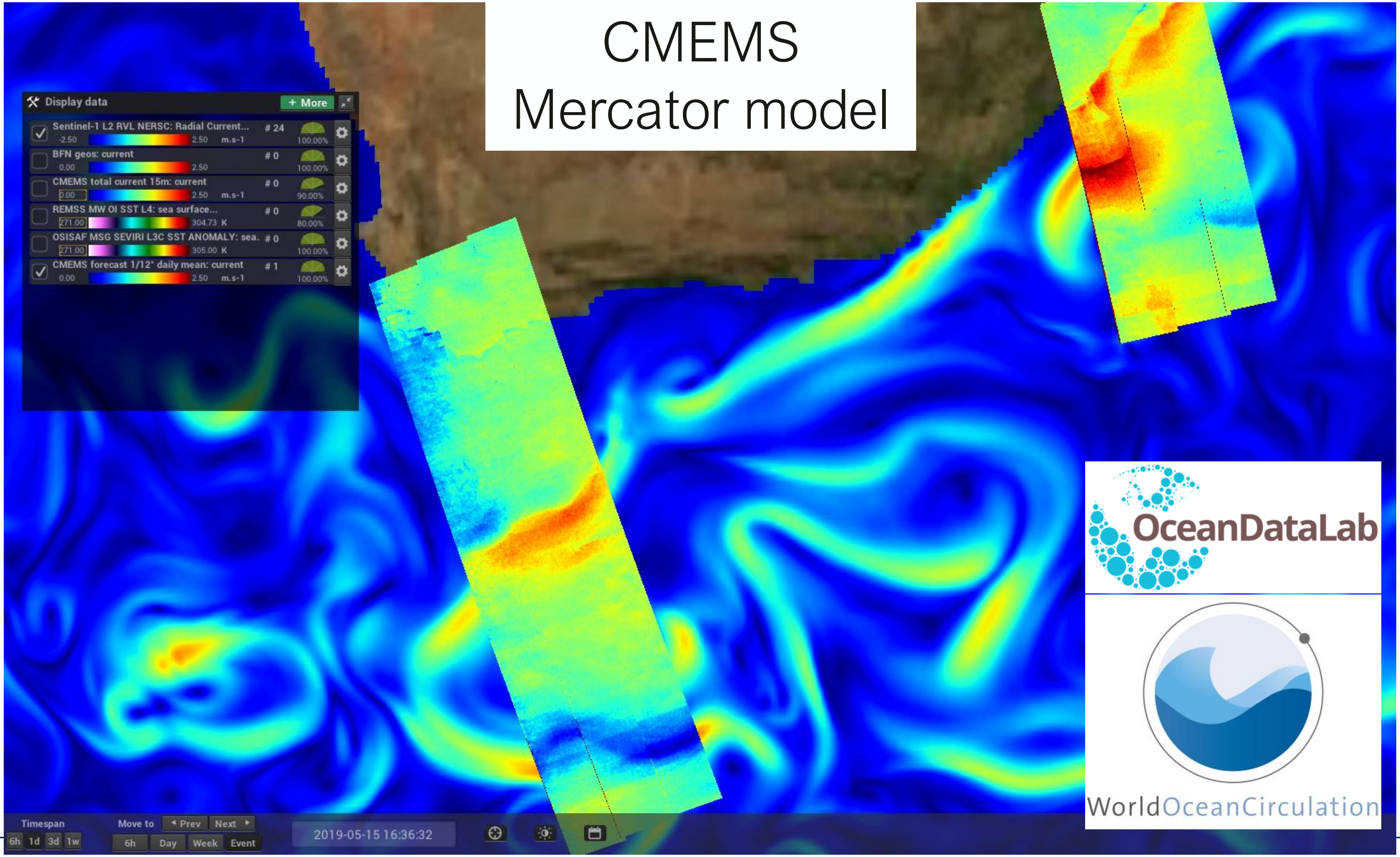

Summary and outlook

Conclusions & perspectives

- Senitnel-1 Doppler provides an opportunity to monitor ocean surface currents in the coastal zones and open ocean

- Two times improvement of the signal precision to 3 – 4 Hz after new calibration (not over)

- Lessons learned from the Senitnel-1 (calibration, GMFs, etc.) can be used in planned and future missions